

Technical Report No. 32-773

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Television Optical System*

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R. A. Becker

H. O. Kruger

H. O. Kruger, Manager
Applied Science Section

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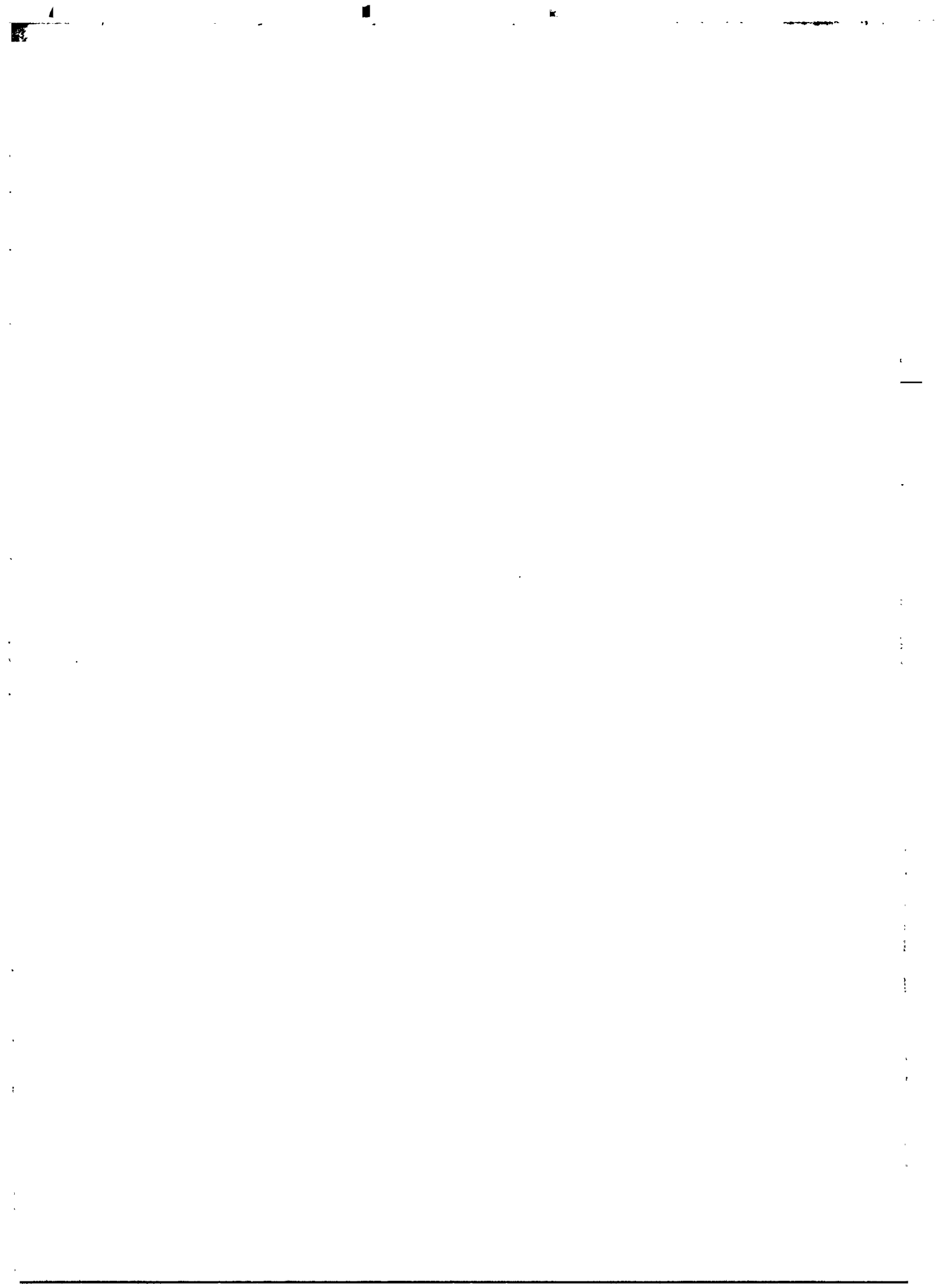
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ABSTRACT

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Reported in this paper are the development and testing of the television optical system for *Mariner IV*. System performance under simulated conditions of launch and space environment are described. Analyses of the specific capability requirements and of the design considerations for such a system are included. Also discussed are the special problems of the filter-shutter mechanism, the selection of lubricants, and the use of nonmetallic materials for certain parts in the system. Expected results of the photographic mission are defined.

Author

I. INTRODUCTION: MISSION PROFILE

The prime objective of the *Mariner IV* flight to Mars is to obtain close-up television pictures of the surface of the planet Mars, then to transmit these pictures back to Earth after the spacecraft has flown behind the red planet and has re-established telemetry communication with Earth.

Launch operations of *Mariner IV* took place on

November 28, 1964. Duration of flight to the Mars-spacecraft encounter will be almost 8 months; the encounter is scheduled to occur at approximately zero hours Greenwich Mean Time on July 15, 1965. As many as 22 television photographs will be taken during the 25 min in which the camera is to scan the planetary surface from the sunlit limb to the darkened sunset terminator.

II. DESIGN AND TEST CONSIDERATIONS

A. Experiment Imaging Requirements

To advance the state of knowledge about Mars significantly, the surface resolution recorded by a Mars fly-by television experiment should be at least one order of magnitude better than that obtainable from Earth. This criterion dictates that the system design should be such as to yield a surface-resolution capability of approximately 5 km or better. Originally, the camera was de-

signed to produce 5-km resolution at a range of 19,000 km. Subsequent redefinition of the flight mission will now permit the camera to photograph the Martian surface at a minimum distance of 11,000 km. This capability will produce a surface resolution of approximately 2.8 km.

The camera is mounted on an instrument platform which rotates about a single axis through the spacecraft

roll axis. Once the planet has come into view, an optical planetary scanner will lock the platform on the proper track across the planet. To ensure that the camera will then be pointing toward the proper place on the planet, it is necessary for the camera alignment to be known and that it remain fixed with respect to the instrument platform. The tolerance on the alignment of the camera line of sight with respect to the platform was set at ± 0.1 deg.

An exposure time of 200 msec can be accommodated by the camera without introducing objectionable image smear as a result of the velocity of the spacecraft relative to the planetary surface. It is desirable to use long exposure times to facilitate taking photographs in the terminator regions where shadow detail may yield clues to the roughness of the Martian surface. Estimates of the surface brightness in the terminator regions led to the selection of $f/8$ as a suitable lens speed for use with the vidicon tube developed for the camera.

The Martian surface is to be photographed in two colors through the use of color filters. One of the color bandpasses peaks at 5400 Å, the other at 6000 Å. Radiation below 5000 Å is excluded from the camera to ensure penetration of the Martian atmosphere. The long-wavelength sensitivity of the camera tube falls to zero at 6700 Å.

The imaging requirements are summarized in Table 1.

Table 1. Experiment imaging requirements

Item	Requirement
Camera system resolution	5 km at 19,000 km range = 0.9 arc min
Optical system resolution (low contrast)	0.2 arc min
Line-of-sight alignment	± 0.1 deg
Optical axis alignment to mechanical axis	± 0.1 deg
Exposure time	0.200 sec max
Relative aperture	$f/8$
Spectral response	Two spectral windows in the visible range above 5000 Å

B. The Space Environment

The space environment for the camera will be relatively comfortable except for vacuum which may go as low as 10^{-10} torr. Anticipated temperatures are in the range of 5 to -12°C , the colder temperatures occurring at the time of planetary encounter. The camera is mounted on the side of the spacecraft away from the Sun and, consequently, is protected from solar radiation. Passive thermal control is provided for the optical system

through the use of low-emissivity gold-plated external surfaces.

Micrometeorite protection was afforded the optical system during the first third of the flight path by a fold-away cover over the instrument platform. This cover was opened on February 10, 1965, for the purpose of increasing the overall spacecraft reliability at encounter. Once it is open, the cover cannot be re-closed.

To determine whether or not the camera design incorporated sufficient design margins to withstand the mechanical loadings that occur during launch operations, a flight-configuration test camera was subjected to the mechanical tests listed in Table 2. These tests were conducted along three orthogonal mechanical axes, one of which is parallel to the thrust axis of the *Atlas-Agena* booster system. Also listed in the Table are two space-environmental tests that were performed to obtain a knowledge of the camera survivability and operation under possible flight-temperature extremes.

Table 2. Mechanical design verification tests

Test	g level, rms	Frequency range, cps	Duration, sec	Tests/axis
Shock	200	—	0.0007 (rise time)	5 shocks
Vibration	20	55-70	5.2	2 sweeps on thrust axis
	30	70-100	7.9	2 sweeps on 2 lateral axes
	12	55-100	13.1	
	14	Noise	18	2 bursts
	5 2 9	Noise 15-40 40-2000	600	2 sweeps concurrent with noise
Static acceleration	± 14	—	300	1 each direction along axis
	Temperature, $^{\circ}\text{C}$		Time	Pressure, torr
Thermal shock	+75 (begin) -46 (end)		2 hr	10^{-4}
Thermal vacuum	-40		4 hr	10^{-4}
	+50		12 days	10^{-4}

C. Cassegrainian Telescope

1. Optical Design Factors

The Cassegrainian-type system was chosen for the television camera on the basis of the following characteristics:

1. The Cassegrainian system has adequate speed and field coverage to meet the imaging requirements.

2. The Cassegrainian system is inherently lightweight in design with mass concentration near the focal plane. The latter feature greatly facilitates mounting the camera to the spacecraft.
3. The Cassegrainian system has a minimum susceptibility to the space environment. It is immune to radiation damage and to temperature influences on refractive index. If used in a closed-tube version, its acceptance angle to micrometeorites is relatively small.

To achieve the required ground resolution with a vidicon scan density of 200 lines/0.22 in., a focal length of 11.7 in. is required by straightforward computation. For convenience, the focal length of the actual optical system has been rounded off to 12 in. The field of view is 1.05 deg square.

The relative aperture is an *effective* $f/8$. That is, the speed is $f/8$ after subtracting the loss due to the secondary mirror occultation. The geometric speed is approximately $f/7$.

2. Mechanical Design and Materials

The mechanical design is shown in Figs. 1 and 2. The optical system and the filter-shutter mechanism are all housed in a gold-plated beryllium-copper stepped cylinder of 0.040-in. wall thickness. Although somewhat heavy, beryllium copper was chosen for the telescope tube structure because of its high thermal conductivity and its close match to the thermal expansion coefficient of the beryllium metal used in manufacturing the mirrors. Pure beryllium, although very light in weight, was not used in the tube structure because of its inherent brittleness.

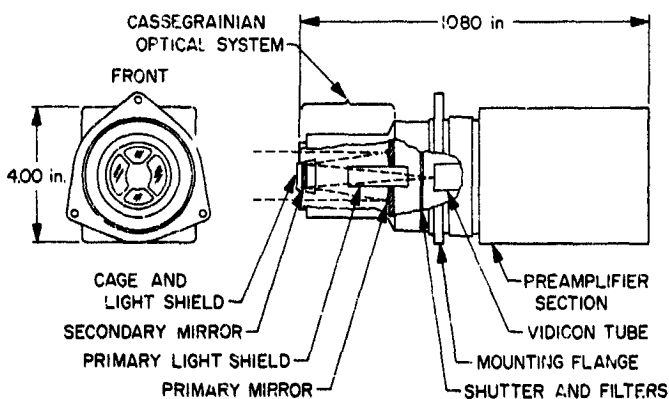


Fig. 1. Components of the vidicon camera head

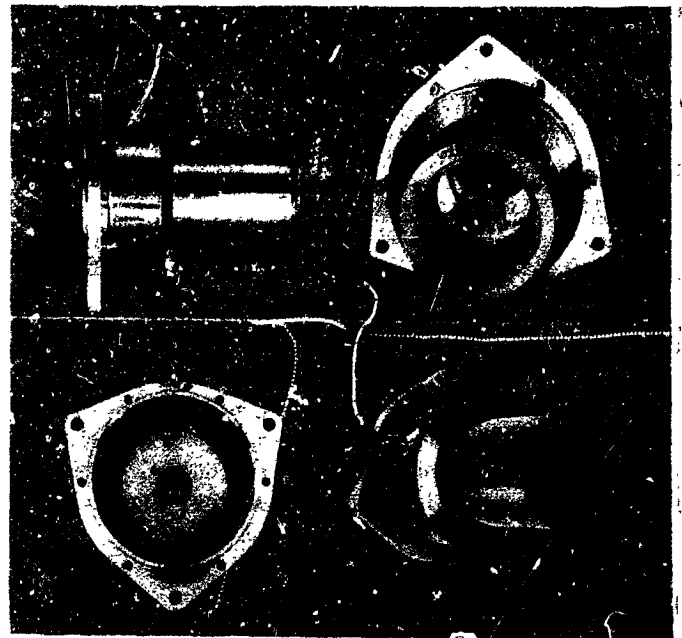


Fig. 2. Four views of a prototype optical system

The beryllium mirrors were machined as closely as possible to the right curvature, ground slightly, then coated with electroless nickel to a thickness of several thousandths of an inch before final grinding and polishing. After the final figure was obtained, the mirrors were aluminized and coated with silicon monoxide.

Characteristic of conventional Cassegrainian optical systems undergoing vibration tests is that at the proper resonant frequency the secondary mirror support system will exhibit a violent rotational mode. This mode can be suppressed effectively through the use of nonradial secondary mirror support vanes, as are shown in Fig. 2.

3. Thermal Design

In order to keep the telescope from defocusing during large temperature excursions, advantage is taken of the fact that a Cassegrainian system, if made completely of materials having the same coefficient of thermal expansion and if not allowed to develop temperature gradient within itself, will merely scale itself, optically and mechanically, with changes in temperature. As mentioned previously, the telescope mirrors and the telescope tube structure are made of materials having approximately the same thermal expansion coefficient. These materials all have high thermal conductivity, which limits temperature gradients within the optical system to a value of approximately 2°C during adverse operating conditions. The use of low-emissivity polished gold plate on the exterior surfaces of the telescope tube further aids in

minimizing temperature gradients by minimizing radiant-heat loss at the exterior surface of the telescope tube.

The calculated focal-shift rate due to the slight mismatch in thermal expansion coefficient between beryllium and beryllium copper is 0.015 in./100°C temperature change. Since we anticipate a deep-space camera operating temperature of -12°C , we expect the focus to change only 0.005 in. from the best focal position established in the laboratory at room temperature. This focal excursion is significantly smaller than the 0.022-in. depth of focus of the camera system. Hence, it is safe to focus the telescope in the laboratory at room temperature for camera checkout purposes without concern for refocusing for the space environment. Since the optical system is a reflecting system, there is no focal shift due to operating in a vacuum.

4. Performance

Two prototype optical systems were built—one for optical performance checks, and one for mechanical testing. One of the prototype systems is shown in Fig. 2. The configuration of the flight-qualified telescopes was identical to that of the prototype system with the exception of a slight change in the three-eared mounting flange in the flight version. The prototype optical system built for optical performance checks yielded a resolution of 87 line-pairs/mm across a total field of view of 1.5 deg when viewing NBS 1952 low-contrast resolution targets. The prototype optical system built for mechanical testing was equipped with unaligned spherical mirrors. Nevertheless, it was found to yield a low-contrast resolution of 60 line-pairs/mm across a 1.5-deg field of view. The five production optical systems, which were constructed for flight operations, were fabricated and tested to a low-contrast resolution of 54 line-pairs/mm, inasmuch as it did not seem necessary to specify an 80-line-pair/mm optical system for an 18-line-pair/mm vidicon tube.

The prototype optical systems were subjected to the severe mechanical levels specified in Table 2. After verifying that the optical system could withstand the mechanical environment, it was tested again in conjunction with the remainder of the television camera. The camera was not operated during the environmental tests listed in Table 2 except during the thermal-vacuum test, but it was operationally checked before and after each type of test to determine the effects of the test on the camera. The optical systems survived all of the tests in operable condition without the need for refocusing or realigning. As a result of the testing, however, minor changes were made in the design of the clamps holding the filters.

Slight chipping had occurred at the edges of the filter glass.

During the thermal-vacuum test, the camera was operated continuously for a period in excess of 12 days at a pressure of approximately 10^{-6} torr. The temperature was -40°C for 4 hr, and was then cycled up to 50°C for 12 days. No operational difficulties were encountered under this environment.

The design verification tests listed in Table 2 were intended to test flight-type equipment to levels greater than those anticipated in the actual flight mission. The exception to this is the vacuum level which is anticipated to be in the order of 10^{-16} torr in interplanetary space and which cannot be readily attained in test chambers. Except for being exposed to the temperature range which was extended to both hotter and colder temperatures than anticipated during flight, equipment built for actual flight operations was tested to less stringent levels than those given in Table 2. On all flight cameras, it was observed that focus of the complete camera system was maintained while the camera head (optics, vidicon tube, preamplifier, and oscillator) went through a temperature excursion from -30 to $+50^{\circ}\text{C}$ in vacuum during a 4-hr period. This is not to say that the optical systems maintained a 54-line-pair/mm resolution during the whole temperature range but that the resolution of the television-camera system did not degrade. The system resolution, with Kell effect considered, is 13 line-pairs/mm.

D. Filter-Shutter Mechanism Development

The design and testing of the *Mariner IV* optical system was more of a mechanical-engineering problem than an optical problem. The part of the optical system that presented the greatest engineering challenge was the filter-shutter mechanism. Inasmuch as the experiment planning required that pictures be taken through the green and orange filters, alternately, and since space available in the optical system was at a premium, it was decided that the operations of shuttering the camera and changing filters should be combined into a single mechanism, hereafter called the shutter.

I. Basic Problems

The basic problems involved in operating a shutter in deep space are lubrication under high-vacuum conditions and the prevention of vacuum coldwelding of atomically clean metal surfaces. These problems could be circumvented by hermetically sealing the shutter. However,

such sealing would introduce two windows into the optical path with their attendant glass-to-metal sealing requirements and would make access to the shutter mechanism for testing and inspection rather difficult. Furthermore, there is always the danger that the seal might not hold the required internal pressure for the complete 8-month flight period. It was finally decided to make a direct attack on the basic problems of lubrication and coldweld in space and to develop an unsealed shutter for *Mariner IV*.

2. Shutter Design and Functions

A general view of the shutter is shown in Fig. 3. The light path is through the aperture in the shutter front plate, through a glass filter in the filter wheel, and thence through an aperture in the shutter rear plate. The shutter is used as a focal-plane shutter, the vidicon tube being located immediately behind the shutter rear plate. The sturdy design of the shutter, which is consistent with the vibration levels anticipated during launch operations, is apparent in the photograph. (The shutter is shown in the closed position.)

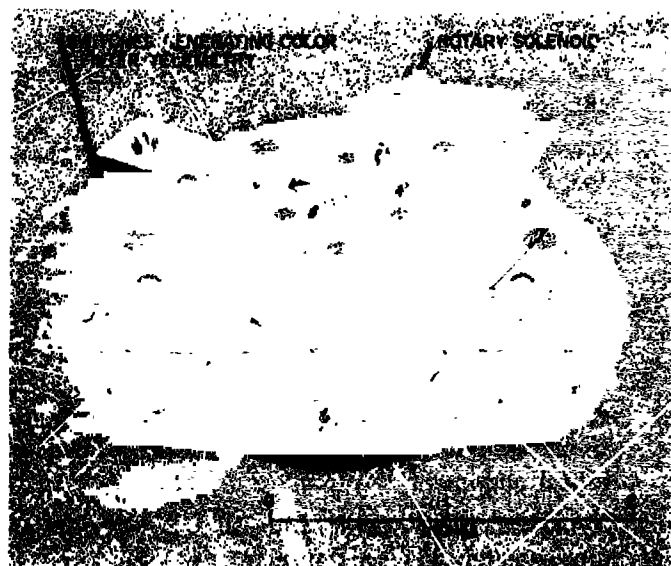


Fig. 3. Flight configuration of the filter-shutter

The actuation cycle of the shutter may be seen in Fig. 4. On the left side of the Figure the shutter is shown in the quiescent, or locked, condition. The condition may occur in either the open- or closed-shutter position, since the filter wheel rotates only 45 deg per actuation and is always locked when not in the process of actuation. A current pulse to the rotary solenoid cocks the shutter as shown in the right-hand side of Fig. 4. Rotation of the

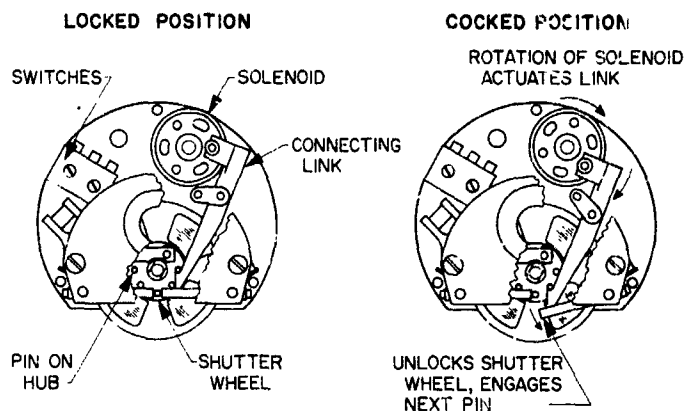


Fig. 4. Diagram showing shutter action

solenoid advances a connecting link so that it simultaneously unlocks the shutter wheel and engages the next pin on the wheel hub. When the current pulse is terminated, the internal solenoid-return spring returns the solenoid and connecting link to their original orientations, advancing the filter wheel 45 deg in the process. The shutter would now be in the open position. A second current pulse (and cocking operation) is required to advance the shutter once again to the closed position.

Two small electric switches, wired in parallel for redundancy, are actuated by a cam-follower arm which follows the cam surface on the shaft of the filter wheel. The primary function of these two switches is to provide information, which will be telemetered to Earth, to give the position of the filter wheel at each camera exposure and, thus, to indicate the color of the filter through which the exposure was made. A second important function of the switches is to provide the same information to the camera-shutter logic circuit for the purpose of electromechanically synchronizing the shutter action during the camera warm-up time and for resynchronizing the action in case the shutter cycle should be upset by a spurious pulse to the solenoid. The electrical function of the switches is to change the filter telemetry signal from a 0 to a 1 condition and back to 0 again as, first, the green and, then the orange filter is placed into the optical path. (See Fig. 5.) The switches are interrogated only between exposures, at which time the 1 condition indicates that a green picture has just been photographed and the 0 condition indicates that an orange picture was most recently exposed.

The shutter is lubricated by the use of dry-film lubrication techniques. All bushings, with the exception of the main solenoid shaft bushing and the solenoid-power take-off shaft bushing, are manufactured from undyed Teflon,

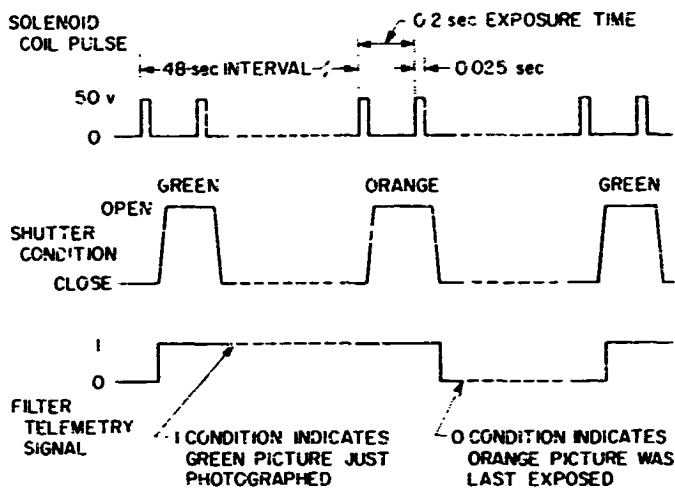


Fig. 5. Timing sequence of shutter-filter action and telemetry

which provides a low coefficient of friction with no apparent possibility of coldwelding to the rotating shafts. The latch-arm sleeves (which lock the shutter wheel in position), the solenoid-power take-off bushing, and the cam-follower wheel are made of molybdenum disulphide impregnated Nylon (Nylatron). This material provides a certain amount of lubrication through the impregnated MoS_2 ; however, its main value here is that it provides a fairly hard nonmetallic substance to separate metallic components which, otherwise, might coldweld under high-vacuum conditions. The connecting link, the filter-wheel hub pins, and the shutter springs are all dry-film lubricated with MoS_2 in a sodium silicate binder. The strength of this dry film is sufficient to prevent sliding metal parts from coming into clean metal-to-metal contact for many thousands of cycles of shutter operation and, hence, the dry film serves as a coldweld preventative, as well as a lubricant. It is preferable to have space-environment-stable plastics (such as Teflon and Nylatron) separating metal moving parts; however, in applications where these plastics do not have sufficient rigidity or strength, the dry-film lubricant mentioned above can serve as a coldweld preventative of somewhat limited life. The solenoid is lubricated entirely by use of the MoS_2 in sodium silicate binder technique.

The problem of outgassing in a space-vacuum environment is critical in space-optical systems, where outgassing products might recondense on optical surfaces or the vidicon faceplate and cause diffusion or absorption of image-forming light. Careful screening of materials to be used in shutter construction was made on the basis of possible outgassing products. In addition, all shutter

components containing Teflon-insulated wire and Nylatron were given a vacuum bakeout to drive off possible volatile materials.

A great deal of mechanical wear is experienced by the shutter mechanism before launch time. Component testing, camera testing and calibration, and finally, spacecraft-systems testing account for roughly 7000 exposure cycles of the shutter before space flight is attempted. As the wear life of MoS_2 dry-film lubricant proved somewhat limited, it was decided to replace the solenoids and connecting links near the end of the testing period to ensure a film thickness sufficient to prevent coldweld during shutter operation especially during the critical time when the spacecraft is in the vicinity of Mars. The replacement of components was made approximately 1500 exposure cycles before the end of testing operations. Thus, the new components were given the opportunity to wear in properly and to demonstrate at least a limited degree of individual-component reliability before the camera was committed to space.

3. Shutter Requirements

The performance requirements imposed upon the shutter design are as follows:

1. The range of exposure times shall be from 80 to 500 msec.
2. The variation of exposure time across the focal plane shall not be greater than 10%.
3. The exposure time shall be repeatable to 10% for a given pulse-time spacing.
4. The repetition rate of the shutter shall be 1 exposure/48 sec.
5. It shall be possible and convenient to maintain the shutter completely open across the 0.22-in.-square format of the vidicon tube for focusing and for optical alignment.
6. The shutter shall operate from 50-v. 30-w pulses of approximately 25-msec duration.

To minimize optical aperture and weight, a rather long exposure time (200 msec) was planned for the photographic mission. The camera has automatic exposure control to the extent that if the integrated video signal exceeds a preset level, the shutter control circuit changes the exposure time from 200 to 80 msec. This process is reversible, so that the camera can again go back to the

¹Dry-film lubrication using MoS_2 works most efficiently after becoming burnished through wear-in.

longer exposure time as the Martian term. is approached. The 48-sec repetition rate of the shutter applies only to camera operation. During testing of the shutter as a component, repetition rates of from 3 to 4 sec were used to conserve testing time.

4. Shutter Testing

All shutters built for flight use were subjected to pre-acceptance tests to determine whether or not they would meet the performance requirements listed above. The five flight shutters were capable of operation under ambient laboratory conditions using pulse levels as low as 37 v. When energized with the specified 50-v pulses, the shutters operated without loss of synchronization at exposure times as short as 69 msec. The repeatability of exposure times at a 200-msec nominal exposure was 4% or better for the various shutters. The uniformity of exposure time across the focal plane was 1% or better for a 200-msec exposure and 3% or better for a 100-msec exposure.

At a temperature of -40°C in vacuum, two of the flight shutters showed approximately 20% variation in exposure times when working in the exposure-time range of 70 to 80 msec. However, these shutters did not lose synchronization with the open and close pulses. At high temperatures (50°C in vacuum and 80°C in air), all the shutters operated in a normal manner.

An extra shutter was fabricated solely for the purpose of conducting shutter life-expectancy testing. This shutter was operated 154,000 exposures before termination of the tests; however, several different types of solenoids and connecting links were used during the life-test program. The final flight-version solenoids were not available for testing until after 138,000 exposures had been accumulated on the life-test shutter. As a result of the life test and supplementary solenoid testing, it was determined that the solenoid is the component that most limits the shutter life. The life expectancy of the shutter is estimated to be of the order of 16,000 exposures.

On February 10, 1965, after *Mariner IV* had been in space for 75 days, a portion of the Mars-encounter photographic sequence was performed. Telemetry received from the spacecraft showed that the shutter operated properly.

E. System Weights

The optical system, minus the shutter, weighs 0.90 lb; the shutter weighs an additional 0.35 lb. Considered part of the optical system, the adapter ring (by which the television camera is bolted to the spacecraft scanning platform) adds 0.22 lb and brings the total optical-system package weight up to 1.47 lb.

III. EXPECTED PERFORMANCE OF MARINER IV OPTICAL SYSTEM

The *Mariner IV* trajectory calculations indicate that the camera will be at a slant range of approximately 16,000 km from the Martian surface when the first television photograph is recorded and approximately 11,000 km when the television camera line of sight crosses the terminator of Mars at the end of the photographic mission. At the 11,000-km range, the field of view will be 202 km square (neglecting some foreshortening). Since the camera makes use of a 200-line scan raster, one television line will correspond to 1.0 km at the planetary surface. Since it takes a minimum of two scan lines for resolution of image detail, the maximum optical resolution is 2.0 km. The probable resolution defined by the Kell effect is 2.8 km. This is a factor of 20 times better than the resolution obtained from Earth-bound telescopes.

The camera will photograph the surface every 48 sec; however, every third photograph will not be transmitted to Earth. This sequencing will result in the photographs being clustered in groups of two. Consecutive photographs in each group will be made through different color channels determined by spectral response of the vidicon tube and the transmission characteristics of Schott glass filters.² Figure 6 shows the vidicon spectral response and the two color channels which result from the product of the spectral response and the transmission of the filter glasses listed in the Figure. It is seen that the system response through the green channel is somewhat

²Each green filter is a combination of a 3-mm thick BG-18 glass plus a 1-mm thick OG-4 glass. The orange filters are 4-mm OG-3 glass.

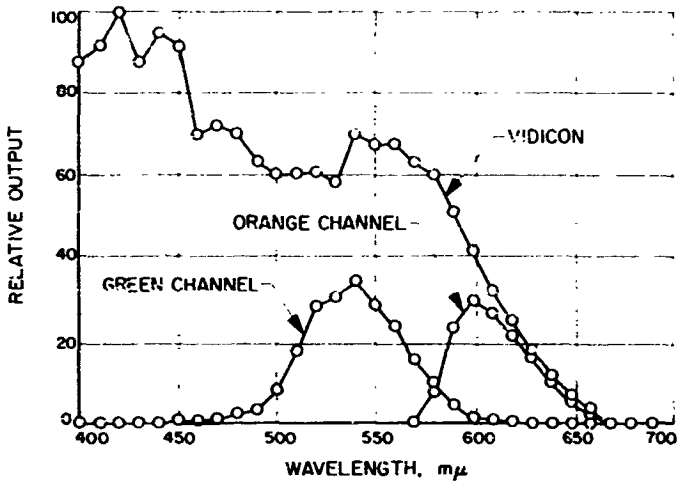


Fig. 6. Television camera spectral response

greater than through the orange channel. This situation compensates, to a degree, for the fact that Mars reflects more orange light than green. Overlap of consecutive fields of view is such that approximately 15% of the area photographed will be seen through both of the color channels. This will aid in gross color identification of the larger surface features.

The path which will be traced by the camera across the surface of Mars is shown³ in Fig. 7. The initial photographic contact will be established in the northern

³The planet is shown in the usual astronomical orientation, i.e., south pole is up.



Fig. 7. Martian area to be photographed

portion of the desert Amazonis. The line of sight (approximated by the two parallel white lines) will then trace south across the desert, crossing Mare Sirenum in the southern hemisphere as the trace becomes parallel with the equator. The photographic mission will conclude at the terminator, where day becomes night on the Martian surface.